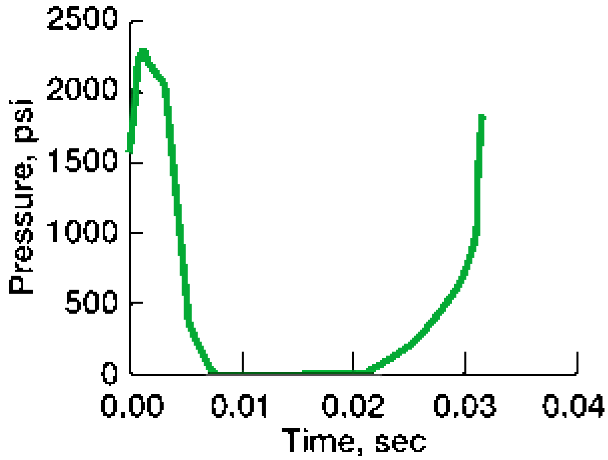
Transient Reliability Analysis Capability Developed for CARES/*Life*

The CARES/*Life* software developed at the NASA Glenn Research Center provides a general-purpose design tool that predicts the probability of the failure of a ceramic component as a function of its time in service. This award-winning software has been widely used by U.S. industry to establish the reliability and life of a brittle material (e.g., ceramic, intermetallic, and graphite) structures in a wide variety of 21st century applications.

Present capabilities of the NASA CARES/*Life* code include probabilistic life prediction of ceramic components subjected to fast fracture, slow crack growth (stress corrosion), and cyclic fatigue failure modes. Currently, this code can compute the time-dependent reliability of ceramic structures subjected to simple time-dependent loading. For example, in slow crack growth failure conditions CARES/*Life* can handle sustained and linearly increasing time-dependent loads, whereas in cyclic fatigue applications various types of repetitive constant-amplitude loads can be accounted for. However, in real applications applied loads are rarely that simple but vary with time in more complex ways such as engine startup, shutdown, and dynamic and vibrational loads. In addition, when a given component is subjected to transient environmental and or thermal conditions, the material properties also vary with time. A methodology has now been developed to allow the CARES/*Life* computer code to perform reliability analysis of ceramic components undergoing transient thermal and mechanical loading. This means that CARES/*Life* will be able to analyze finite element models of ceramic components that simulate dynamic engine operating conditions. The methodology developed is generalized to account for mate-rial property variation (on strength distribution and fatigue) as a function of temperature. This allows CARES/*Life* to analyze components undergoing rapid temperature changein other words, components undergoing thermal shock. In addition, the capability has been developed to perform reliability analysis for components that undergo proof testing involving transient loads. This methodology was developed for environmentally assisted crack growth (crack growth as a function of time and loading), but it will be extended to account for cyclic fatigue (crack growth as a function of load cycles) as well.

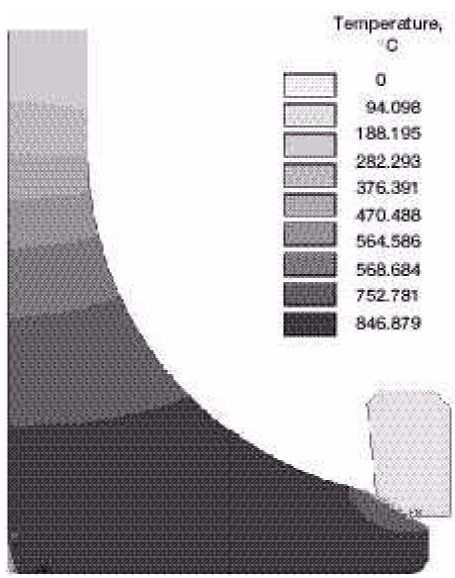
An example involving a ceramic exhaust valve subjected to combustion cycle loads is presented to demonstrate the viability of this methodology and the CARES/*Life* program. The valve is designed to be used in heavy duty diesel engines. Replacement of the metal exhaust valves with ceramic valves would prolong valve life and permit higher operating temperatures. The valves were made of NT-551 silicon nitride material. Simple specimens (four-point-bend rectangular bars, four-point-bend cylindrical bars, and tensile specimens) were tested in fast fracture and dynamic fatigue modes to extract the Weibull and slow crack growth parameters for NT-551 as a function of temperature. These parameters were used to predict the probability of failure of the valve versus the number of operating cycles. For this example, the valves were assumed to degrade because of slow crack growth and not significantly from cyclic fatiguewhich is typical behavior for many ceramic

materials. The following figure represents one pressure cycle applied to the valve face.



Pressure variation applied to the face of a ceramic valve during a typical engine combustion cycle.

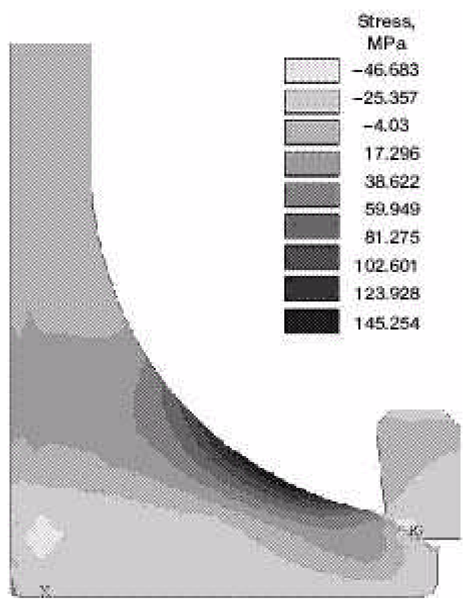
The pressure is applied to the valve's face and other exposed surfaces within the cylinder. In addition, thermal stresses due to the temperature distribution in the valve are superposed to the mechanical stresses. The next figure shows the approximate mean thermal profile in the valve. Steady-state thermal analysis using the ANSYS finite element analysis code was conducted to compute these temperatures. This figure shows that the temperature is maximum near the valve face and decays towards the valve seat and stem.



Mean thermal profile in the ceramic diesel exhaust valve.

The transient reliability analysis was conducted by dividing the load history into 29 time steps; during each, the load was assumed to be constant. The loads corresponding to these time steps were modeled into ANSYS finite element analysis code, which yielded the stress results for these 29 time steps (stress history). The following figure highlights the first principal thermomechanical stress distribution in the valve at the moment of maximum

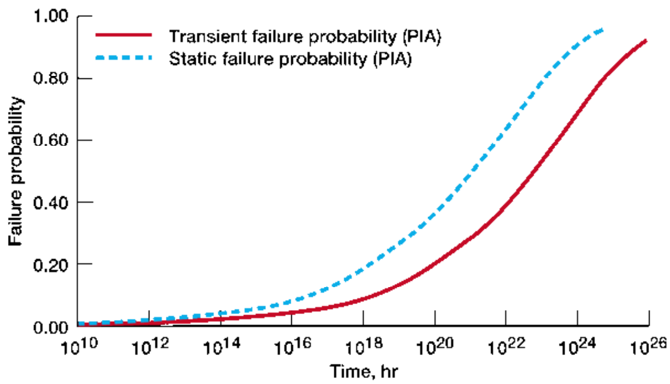
applied pressure (the most critical point of the load history). From the figure, it is apparent that the maximum stress location is at the valve radius. The valve's stress history and other relevant terms (temperature, volume, material properties, element number, etc.) were subsequently read into CARES/*Life*. The failure probability as a function of time (number of cycles converted to time according to 1 cycle = 0.0315 sec) was then computed using the transient reliability analysis described previously. The final figure shows the transient reliability curve as a function of time (load cycles). As can be seen from that figure, the probability of failure increases with time. It is apparent from the figure that this ceramic valve is very reliable. After 1 hr of operation, the failure probability P_f is predicted to be 6310^{-5} (6 in 100,000 valves would have failed), whereas after 8.7 million hr of operation the P_f would be 9.4×10^{-4} (approximately 9 in 10,000 valves would have failed). A static reliability analysis using the maximum load level (load step 6 in this analysis) during the load cycle was performed and compared with the transient reliability analysis based on the actual transient loading.



First principal stress distribution in the diesel exhaust valve at the moment of maximum applied pressure.

The final figure contains the results of this analysis. As can be seen from this figure, the static loading at the maximum level yielded higher failure probabilities (more conservative) in comparison to the transient loading case. Between 9 and 9×10^{15} hr of operation, the failure probability based on static analysis at maximum stress is double the failure probability based on transient analysis. For example, after 1000 hr of operation, transient reliability analysis predicted that approximately 2 in 10,000 valves would have failed, whereas maximum static reliability analysis predicted that approximately 4 in 10,000 valves would have failed. These results, showing higher failure probabilities for the static loading compared with the transient loading, make sense since the valve is not even loaded for some time during each combustion cycle. Therefore, depending on the structure and loading, making the assumption that static reliability analysis at the maximum load level can produce close results using the actual loading is not always accurate. Such static

analysis can lead to overdesigned structures.



Transient and static probability of failure as a function of time for the ceramic valve. PIA, principle of independent action.

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